Pauli exclusion principle: wave function for identical fermions must be **antisymmetric** if the particle labels are exchanged

How do we tell what symmetry the isospin configurations have? I = 0 or 1 for NN.

Use symbolic representation: $\uparrow = \frac{1}{2}$ and $\downarrow = -\frac{1}{2}$

The 4 configurations (m_1, m_2) are: $(\uparrow\uparrow)$, $(\uparrow\downarrow)$, $(\downarrow\uparrow)$, $(\downarrow\downarrow)$

$(\uparrow\uparrow)$ and $(\downarrow\downarrow)$ are **symmetric** – exchanging the symbols (1,2) has no effect. These correspond to total isospin $(I, m_I) = (1, 1)$ and $(1, -1)$

$(\uparrow\downarrow)$, $(\downarrow\uparrow)$ states correspond to $m_I = 0$, but they have **mixed symmetry**. ☹

Solution: make symmetric and antisymmetric combinations of the mixed states:

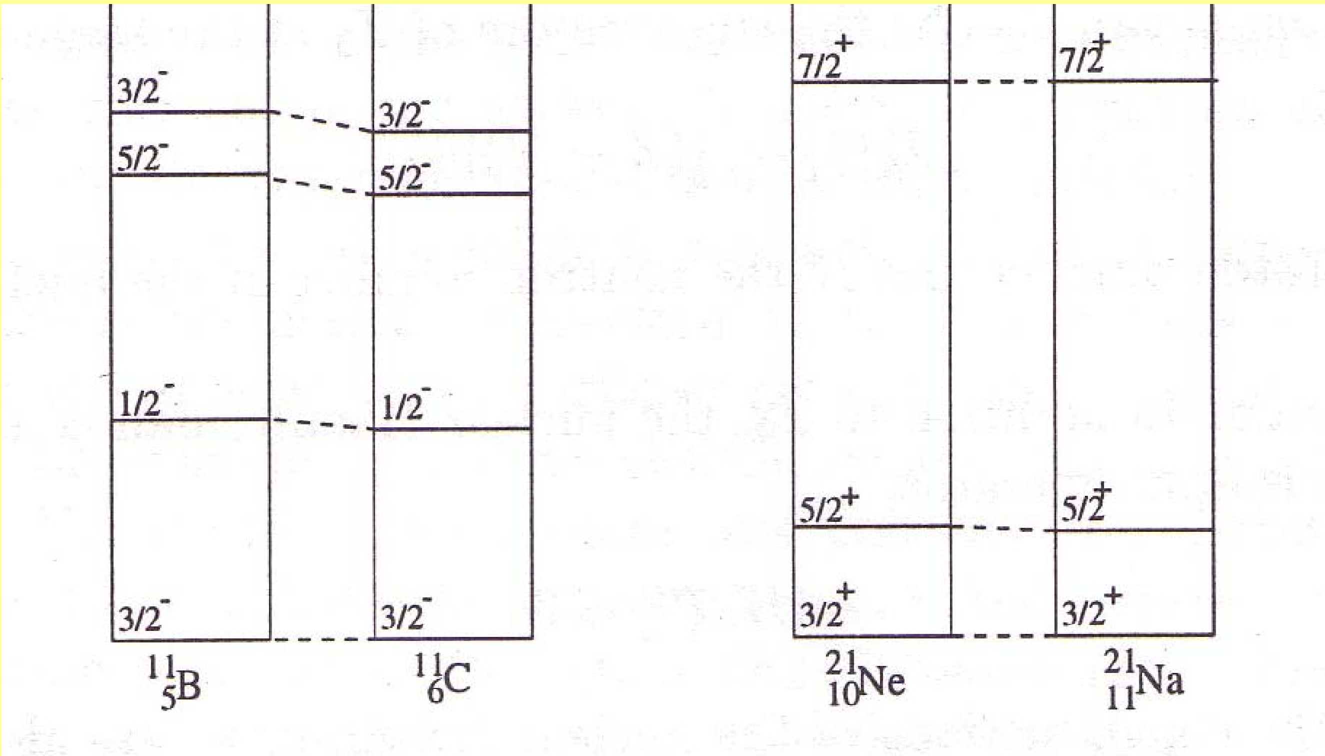
symmetric: $(\uparrow\downarrow) + (\downarrow\uparrow) \rightarrow (\downarrow\uparrow) + (\uparrow\downarrow)$ **$(I=1,\ m_I = 0)$**

anti – : $(\uparrow\downarrow) - (\downarrow\uparrow) \rightarrow (\downarrow\uparrow) - (\uparrow\downarrow) = -\{(\uparrow\downarrow) - (\downarrow\uparrow)\}$ **$(I=0,\ m_I=0)$**

Bottom line: **I** = 1 states are symmetric, I = 0 antisymmetric. (Same for spin, S)
The np system can be in a state of either I = 1 or I = 0 but not both, if isospin is a good quantum number.

- Nucleon: $I = \frac{1}{2}$, $m_I = \pm\frac{1}{2}$. For a **nucleus**, by extension: $m_I = \frac{1}{2}(Z - N)$.
- If neutrons and protons are really "identical" as far as the strong interaction is concerned, then nuclei with the same mass number but (Z,N) interchanged ought to be very similar. These are called "**mirror nuclei**", e.g. ^{11}B (5,6) and ^{11}C (6,5)
- Energy spectra line up after correction for Coulomb energy difference in the ground state. ✓

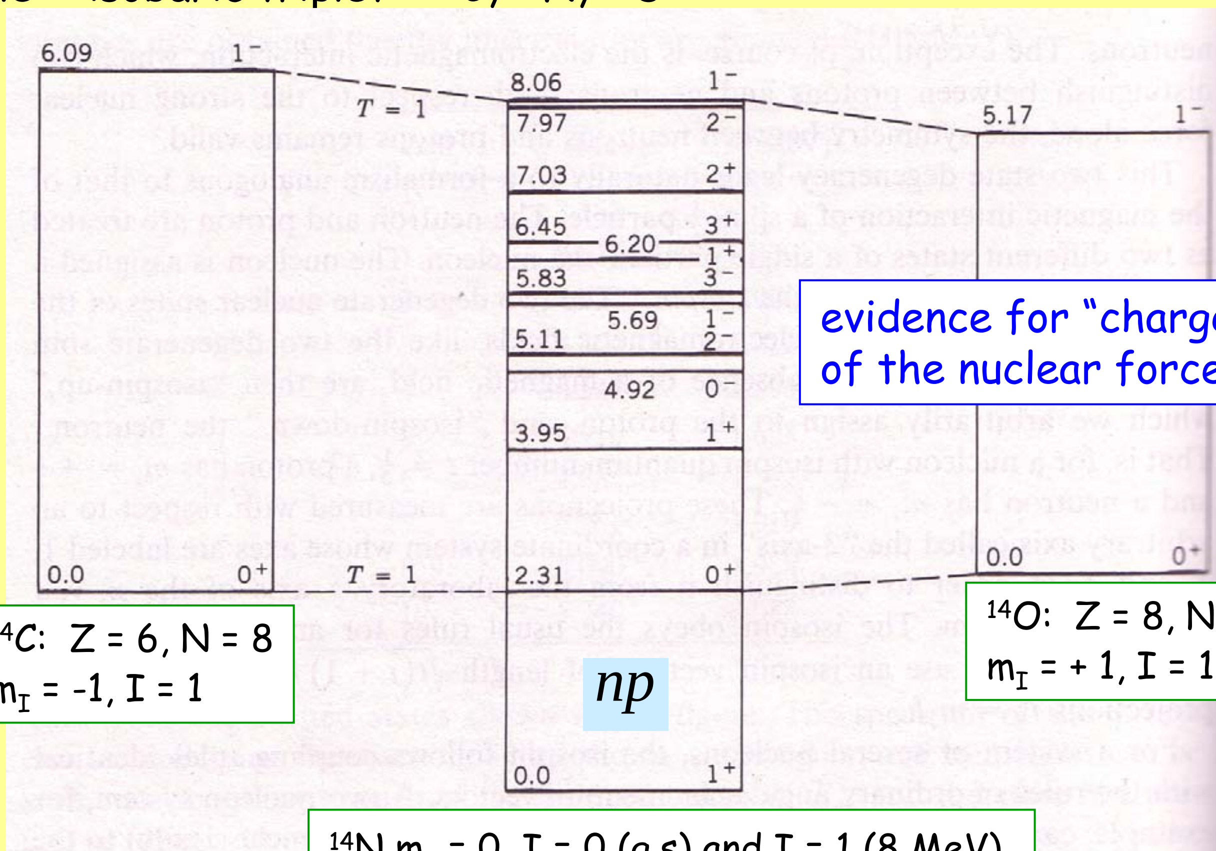
evidence for "charge symmetry" of nuclear force



implications of isospin symmetry:

(note – other convention: T = isospin)

- pp and nn systems are always I = 1
- np system is (↓↑) , ie it can be partly I = 1 and partly I = 0
- for a **nucleus**, $m_I = \frac{1}{2}(Z-N)$ and $I = |m_I|$, ie lowest energy has smallest I
  (consistent with the deuteron being I = 0)
- Example: "isobaric triplet" ^{14}C, ^{14}N, ^{14}O:



evidence for "charge independence" of the nuclear force

nn

^{14}C: Z = 6, N = 8
$m_I = -1$, I = 1

np

^{14}O: Z = 8, N= 6
$m_I = +1$, I = 1

pp

^{14}N $m_I = 0$, I = 0 (g.s) and I = 1 (8 MeV)

Consider the deuteron, ^{2}H = (np) bound state (d)

Quantum numbers: $m_I = 0$, $I = 0$ $J^\pi = 1+$ ($S = 1$, $L = 0$, $\pi = (-1)^L$)

How do we know it has I = 0 ?

"Isospin selection rules":

The reaction: 1) d + d $\rightarrow$ γ + ^{4}He occurs, but

isospin analysis: $\vec{0} + \vec{0} = \vec{0} + \vec{0}$ (I = 1 deuteron also works)

2) d + d $\rightarrow$ π° + ^{4}He does not

isospin analysis: $\vec{0} + \vec{0} \neq \vec{1} + \vec{0}$ (only I = 0 prevents this!)

Bottom line: I is conserved by the strong interaction. Energy depends on I but not on m_I

News flash from Indiana University:

VOLUME 91, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2003

Observation of the Charge Symmetry Breaking $d + d \rightarrow {}^4\mathrm{He} + \pi^0$ Reaction Near Threshold

E. J. Stephenson,[1] A. D. Bacher,[1,2] C. E. Allgower,[1] A. Gårdestig,[3] C. M. Lavelle,[1] G. A. Miller,[4] H. Nann,[1,2] J. Olmsted,[1] P. V. Pancella,[5] M. A. Pickar,[6] J. Rapaport,[7] T. Rinckel,[1] A. Smith,[8] H. M. Spinka,[9] and U. van Kolck[10,11]

[1]*Indiana University Cyclotron Facility, Bloomington, Indiana 47408, USA*
[2]*Department of Physics, Indiana University, Bloomington, Indiana 47405, USA*
[3]*Indiana University Nuclear Theory Center, Bloomington, Indiana 47408, USA*
[4]*Department of Physics, University of Washington, Seattle, Washington 98195, USA*
[5]*Physics Department, Western Michigan University, Kalamazoo, Michigan 49008, USA*
[6]*Department of Physics and Astronomy, Minnesota State University at Mankato, Mankato, Minnesota 56001, USA*
[7]*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA*
[8]*Physics Department, Hillsdale College, Hillsdale, Michigan 49242, USA*
[9]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[10]*Department of Physics, University of Arizona, Tucson, Arizona 85721, USA*
[11]*RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA*

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We report the first observation of the charge symmetry breaking $d + d \rightarrow {}^4\mathrm{He} + \pi^0$ reaction near threshold. Measurements using a magnetic channel (gated by two photons) of the ^{4}He scattering angle and momentum (from time of flight) permitted reconstruction of the π^0 "missing mass," the quantity used to separate $^4\mathrm{He} + \pi^0$ events from the continuum of double radiative capture $^4\mathrm{He} + \gamma + \gamma$ events. We measured total cross sections for neutral pion production of 12.7 ± 2.2 pb at 228.5 MeV and 15.1 ± 3.1 pb at 231.8 MeV. The uncertainty is dominated by statistical errors. These cross sections arise fundamentally from the down-up quark mass difference and quark electromagnetic effects that contribute in part through meson mixing (e.g., $\pi^0 - \eta$) mechanisms.

Tour-de-force experiment: http://www.cerncourier.com/main/article/43/5/4

$d + d \rightarrow {}^4\mathrm{He} + \pi^{\mathrm{o}}$???

- isospin-forbidden reaction since I = 0 for the d, ^{4}He, and I=1 for π^o: "textbook case"

  *(technically speaking, this reaction breaks "**charge symmetry**" which is the symmetry under reversal of all up and down quarks in a wave function, or equivalently a quark "isospin flip". The pion wave function is CS – odd; the others are CS even)*

- Charge symmetry is broken by the electromagnetic interaction: up-down quark mass difference, and their electric charge differences

- reaction could proceed with very low cross section compared to isospin-allowed cases, but there was never any convincing evidence published until 2003

- compare similar cross-sections at reaction threshold:

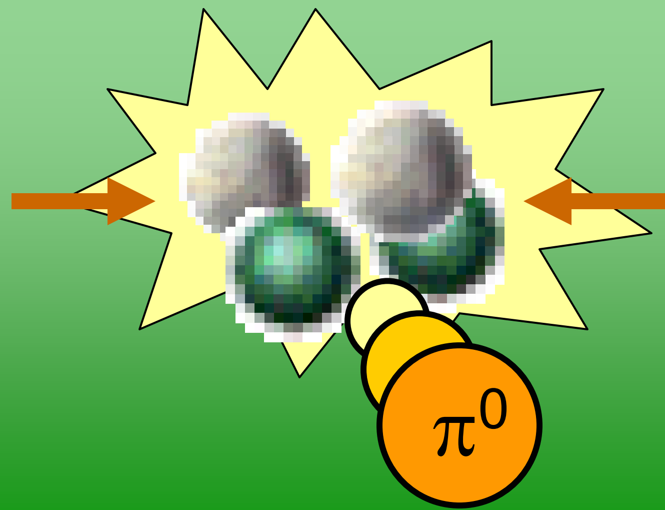
$p + d \rightarrow {}^3\mathrm{He} + \pi^o$	σ = 13 μ**b**	(Isospin allowed)
$d + d \rightarrow {}^4\mathrm{He} + \pi^o$	σ = 13 $\pm$ 2 **pb**	(forbidden, new result)

- Rough estimate of cross section ratio :

$$\sigma \sim \left(\int \psi_f \; V \; \psi_i \; d^3 r \right)^2 \quad \Rightarrow \quad \frac{\sigma_{allowed}}{\sigma_{forbidden}} \sim \left(\frac{V_S}{V_{em}} \right)^2 = \left(\frac{1}{4\pi\varepsilon_0 \hbar c} \right)^2 \approx 2 \times 10^4 \quad ?$$

Comparison of precise measurement and theory, accounting for all known CSB effects, tests our understanding of CS as a symmetry of the strong interaction

Cooler CSB



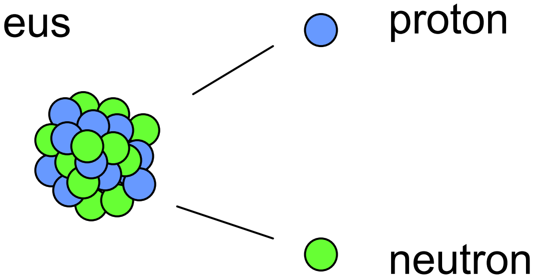
the search for $d+d \rightarrow \alpha\pi^0$

slides courtesy of Dr. E. Stephenson, Indiana University

Ed Stephenson
Physics Colloquium
9/24/03

full set: http://www.iucf.indiana.edu/Experiments/COOLCSB

atomic nucleus

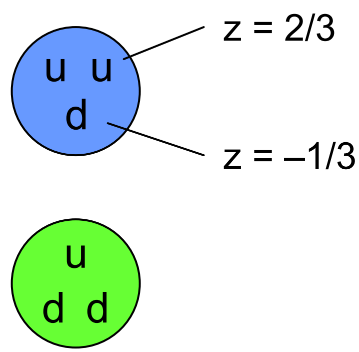


Simple notion: <u>charge symmetry</u>
The proton and neutron are the same except for electromagnetic properties.

Isospin: the quantum number for CS
Proton and neutron have *I = 1/2*

But they are different: $m_N - m_P = 1.3$ MeV
(The neutron decays in 887 s: $n \rightarrow p + e^- + \bar{\nu}_e$)

quarks inside nucleons: CS says up and down are the same except for charge



Nuclear charge symmetry breaking comes from:

- electromagnetic interactions among quarks
- $m_d > m_u$

How much does each contribute?

Observation of the Isospin-forbidden $d+d \rightarrow {}^4He+\pi^0$ Reaction near Threshold

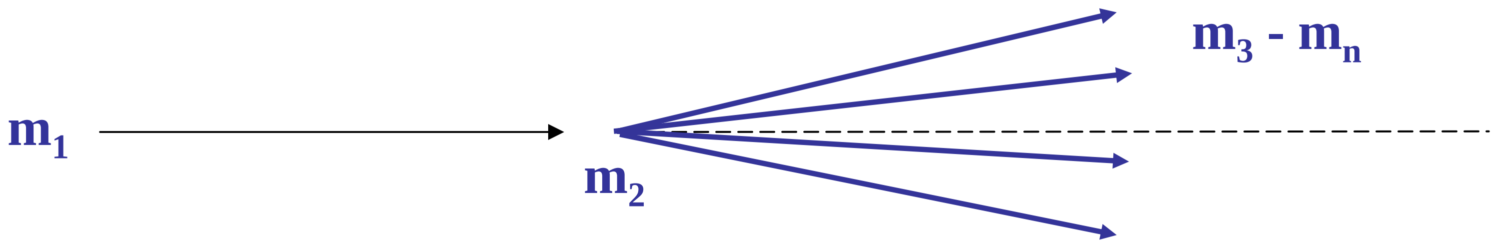
$$d + d \Rightarrow {}^4He + \pi^0$$

isospin: 0 0 0 1

CHARGE SYMMETRY says that the physics is unchanged when protons and neutrons are swapped, or when up and down quarks are swapped.

The pion wavefunction $\psi = \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right)$ is not symmetric under up-down exchange. Deuterons and helium reverse exactly. Thus, an observation of this process is also an observation of charge symmetry breaking.

Threshold Energy:



For a reaction to occur in a fixed target experiment, m_1 has to hit m_2 with enough energy to make the particles in the final state. The minimum kinetic energy required is called the threshold energy:

$$T_{thr} = -Q\,\frac{m_1 + m_2 + \Sigma m_f}{2m_2}$$

$$Q = m_1 + m_2 - \Sigma m_f$$

Relativistic formulation! Next homework...

Examples:

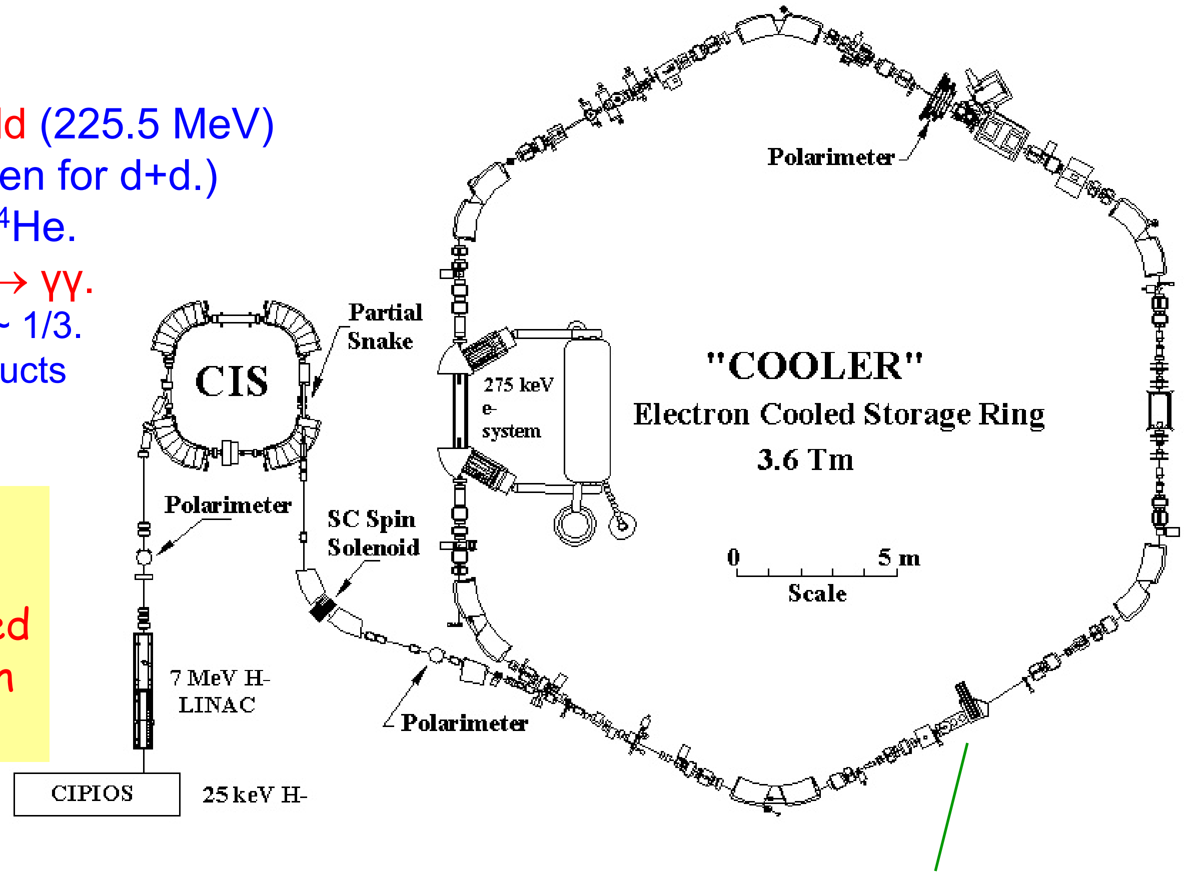
$$d + d \longrightarrow \alpha + \pi^0 \qquad T_{thr} = 225.4\ \text{MeV}$$

$$p + d \longrightarrow {}^3He + \pi^0 \qquad T_{thr} = 198.7\ \text{MeV}$$

Experimental approach:

Search just above threshold (225.5 MeV)
- (No other π channel open for d+d.)
- Capture forward-going ^{4}He.
- Pb-glass arrays for $\pi^0 \rightarrow \gamma\gamma$.
  - Efficiency on two sides ~ 1/3.
  - Insensitive to other products
    - (γ_{beam} = 0.51)

Pb-glass measures photon energy via Cerenkov light from high energy e- produced in a 'shower' initiated by high energy photon collisions

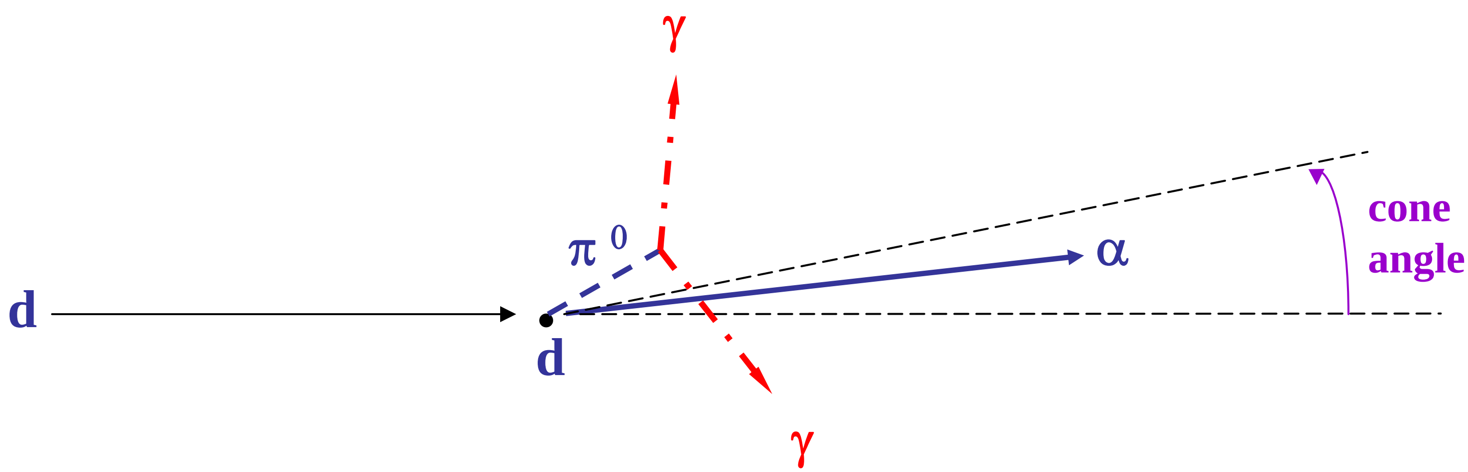


Target density = 3.1 x 10^{15}
Stored current = 1.4 mA
Luminosity = 2.7 x 10^{31} /cm^2/s

Expected rate ~ 5 /day

6° bend in Cooler straight section
- Target upstream, surrounded by Pb-glass
- Magnetic channel to catch ^{4}He (~100 MeV)
- Reconstruct kinematics from channel
  - time of flight and position.

$d + d \longrightarrow \alpha + \pi^0$ in the lab close to threshold:



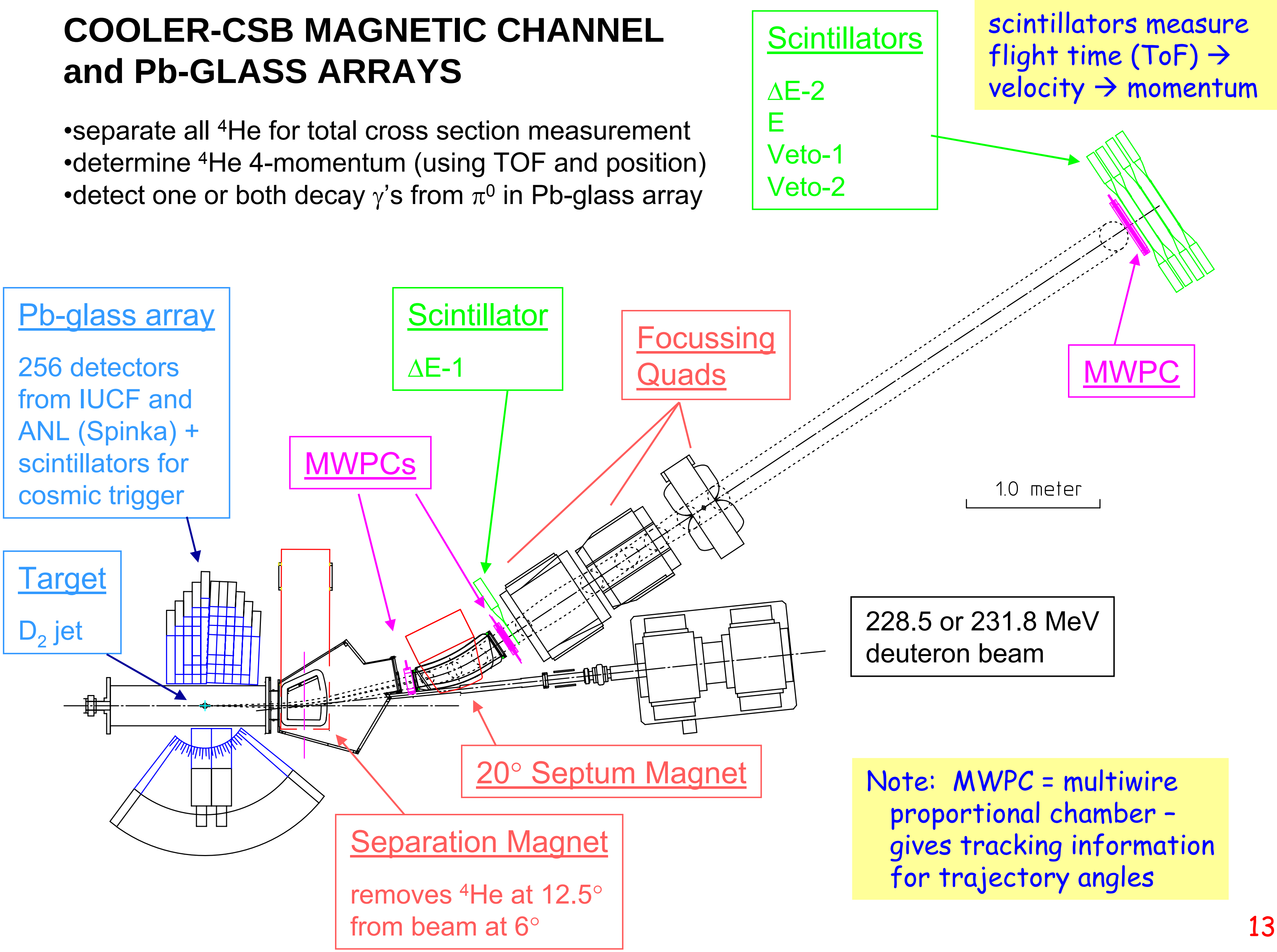
For a fixed target experiment just above threshold,

- α particles emerge within a narrow cone about the 0-degree line. (Spectrometer with small forward acceptance will catch every α.)
- low-energy π^0 quickly decays into two photons which emerge nearly back to back in the lab.

Therefore, the apparatus must identify a forward α in coincidence with two photons that have a large opening angle between them.

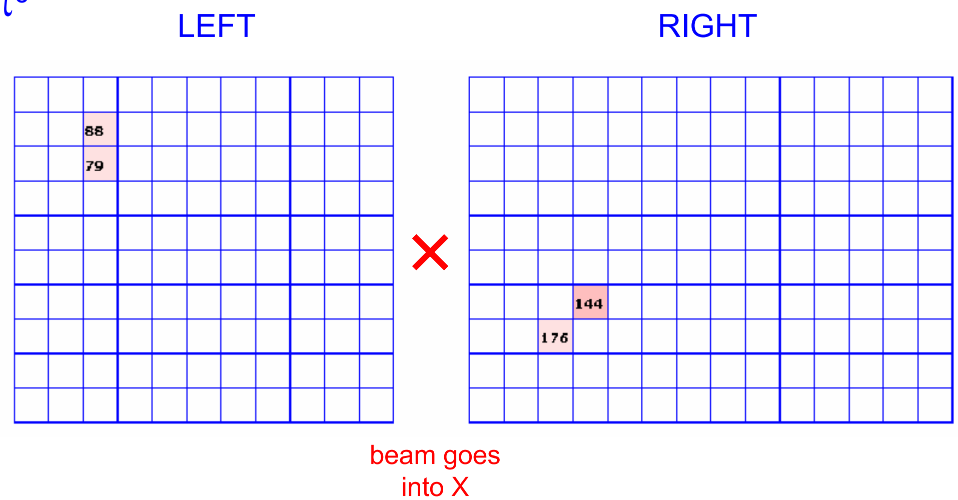
COOLER-CSB MAGNETIC CHANNEL and Pb-GLASS ARRAYS

- separate all ^{4}He for total cross section measurement
- determine ^{4}He 4-momentum (using TOF and position)
- detect one or both decay γ's from π^0 in Pb-glass array

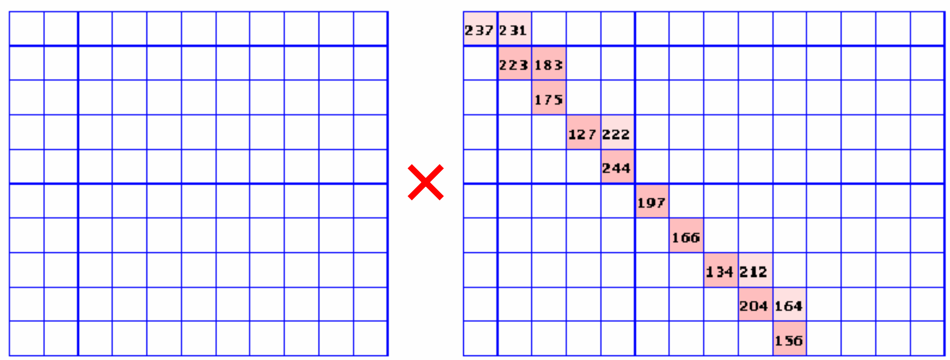


$\pi^0 \rightarrow \gamma\gamma$ from p+d $\rightarrow$ ^{3}He+π^0

Pb-glass Hit Patterns



cosmic ray muon



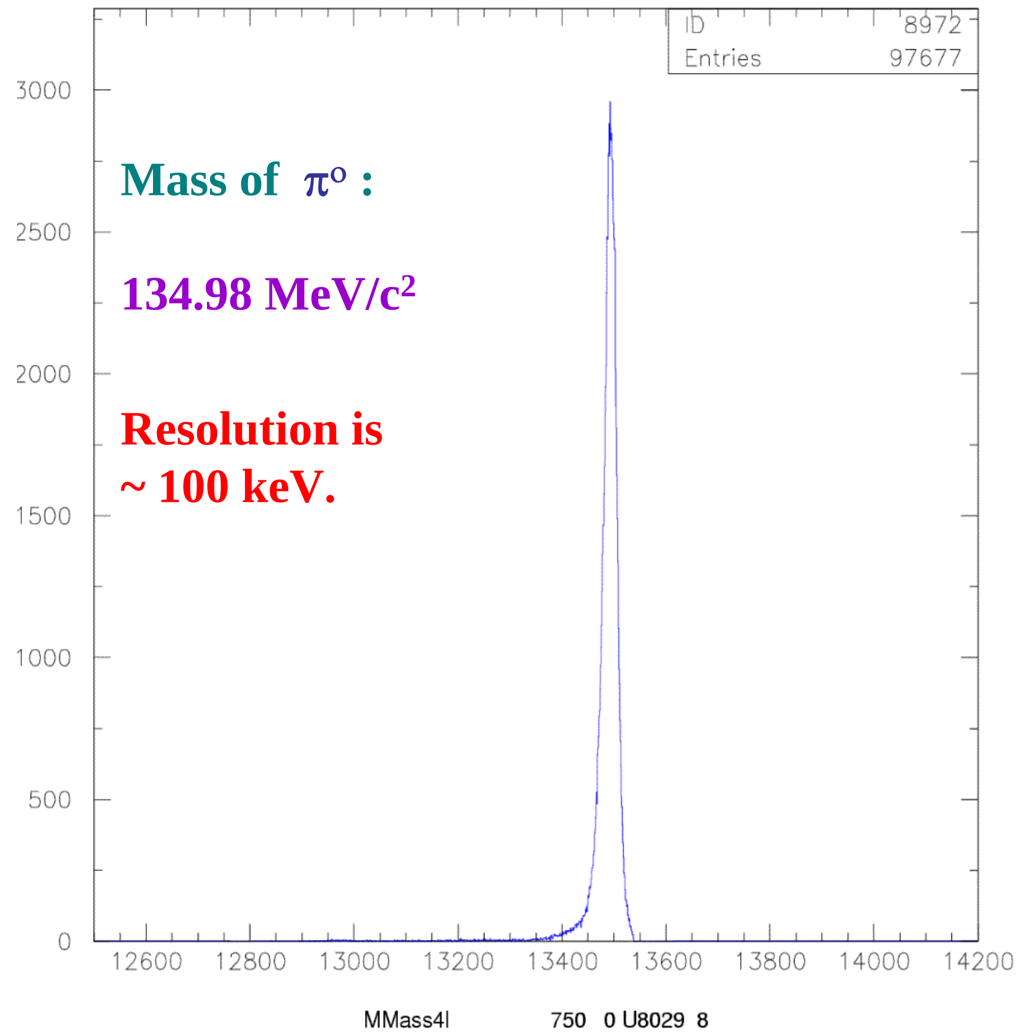
color scale: red > pink > blue

`Missing Mass' measured with proton beam: $p + d \rightarrow {}^3He + \pi^o$

conservation of energy:

$W \equiv E_p + E_d - E(^3He) = m_\pi$

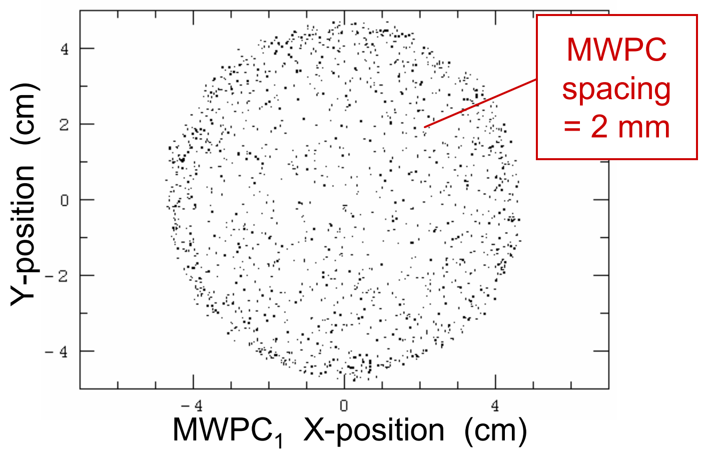
- E_p from beam energy
- deuteron at rest in target
- $E(^3He)$ from energy and momentum measured with the magnetic channel
- calculate W from data, should find a peak at the pion mass for reaction at threshold.
- then check in Pb glass array to see if pion was observed

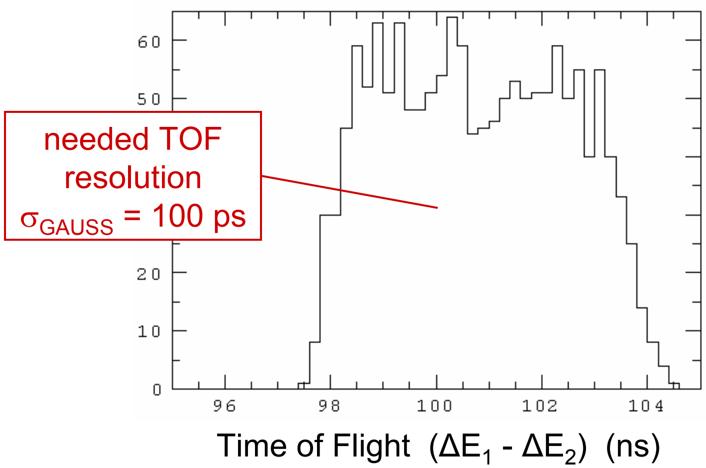


Mass (Mev/c^2 * 100)

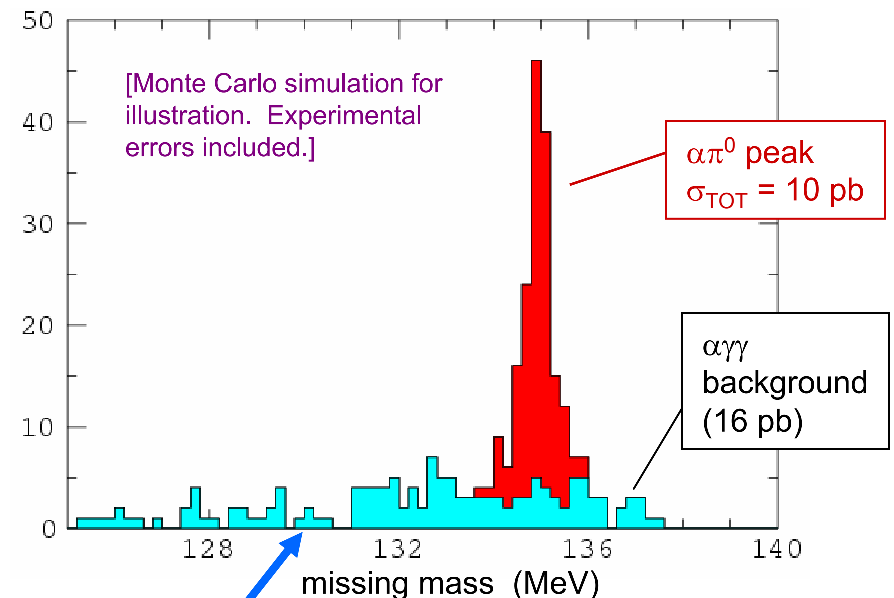
SEPARATION OF $\alpha\pi^0$ AND $\alpha\gamma\gamma$ EVENTS

IDEA: Calculate missing mass from the four-momentum measured in the magnetic channel, using time-of-flight for z-axis momentum and MWPC X and Y for transverse momentum. Should see a peak for $\alpha\pi^0$ reaction and a broad background from $\alpha\gamma\gamma$



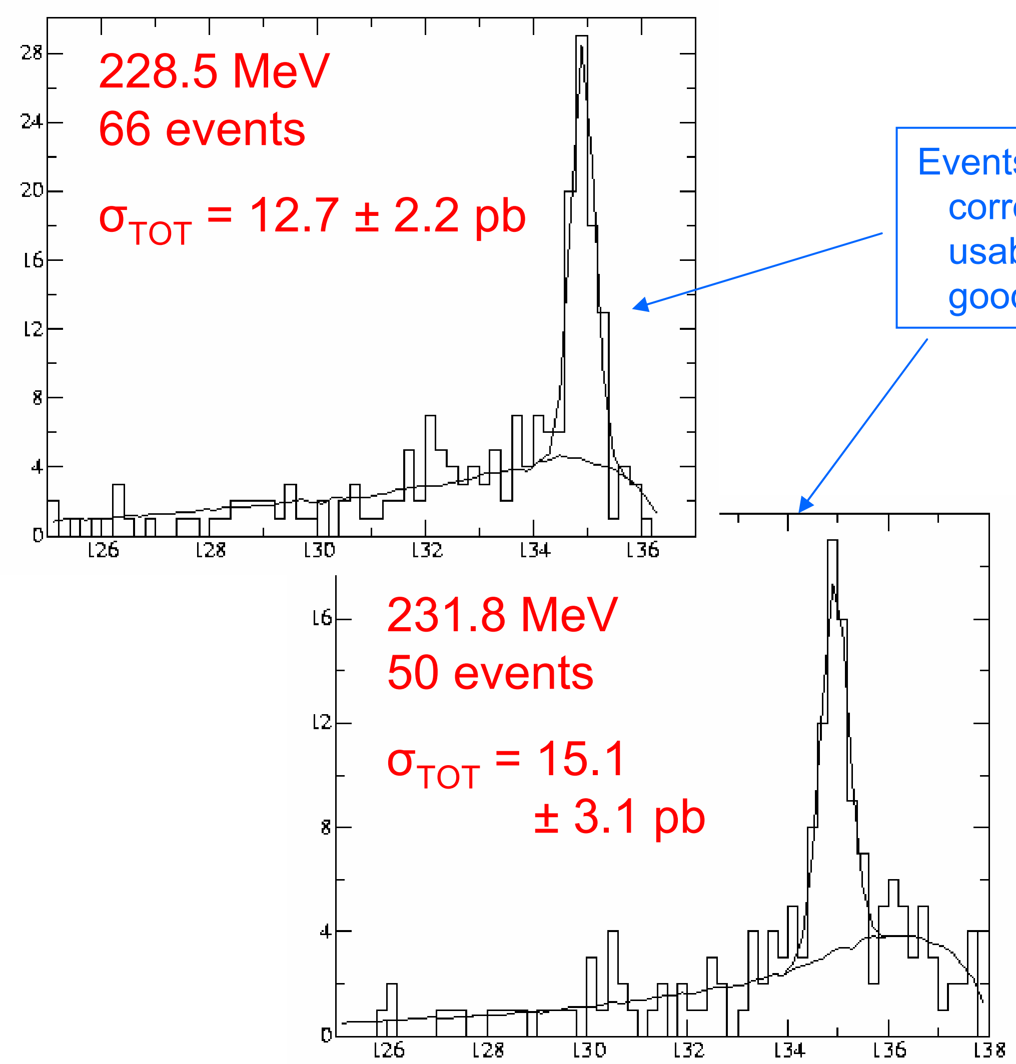


Need very good resolution so that the peak is detectable!



Background: $d + d \rightarrow \alpha + 2\gamma$

RESULTS *(measured at two different beam energies)*



missing mass (MeV)

Events in these spectra must satisfy:
- correct pulse height in channel scintillators
- usable wire chamber signals
- good Pb-glass pulse height and timing

First ever convincing observation of both the $\alpha\pi^\circ$ and $\alpha\gamma\gamma$ reactions!

Peaks give the correct π^0 mass with 60 keV error. ✓

Bottom line: time to revise all the textbooks!!!